Localization errors with 40-channel tangential fields

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1 Introduction

Multichannel MEG systems measure neuromagnetic fields simultaneously at many scalp locations. By solving inverse problem in adequate algorithm, the location of the current sources responsible for the measured field distribution can be determined non-invasively [1]. In order to study cortical activities of the human brain with MEG systems, the localization accuracy is an important figure of merit of a system.

In the following, we introduce the localization results of our 40-channel SQUID system. The difference between our system and others is that it has integrated DROS (double relaxation oscillation SQUID) planar gradiometers instead of axial gradiometers with conventional dc SQUID. The planar gradiometers are oriented to measure tangential components to the body surface [2]. In this configuration the magnetic field distribution has a peak just above the current dipole and therefore a less extensive sensor array is needed to get the essential field distribution. Also it is quite easy to fabricate planar gradiometers and to get high initial balancing compared with wire-wound pickup coil.

With this system, we determined the criteria so as to obtain a limited location error. To do this, computer simulations were made assuming a dipole in a spherical conductor model. In the model, an axial gradiometer measuring radial fields neglects volume current contributions. On the other hand, tangential fields include the volume current contributions. It has been reported that the fields of spontaneous brain activities are the main source of the background noise in the evoked field response and can be represented by the prestimulus field [3]. In the simulations, we added measured spontaneous brain fields to dipole fields as the background noise so that the obtained results can be applied to the localization of evoked field responses. The calculated dipole parameters were examined in terms of residual noise variance, noise-to-signal ratio and confidence volume to determine localization accuracy. The location accuracy was also determined experimentally using a phantom head.

2 Methods

2.1 40-channel system

Two sets of 20 gradiometers were arranged in a 5×4 and 4×5 rectangular matrix with 22~25 mm spacing, where each set detects B_x and B_y. The gradiometers were located on a plane parallel to the bottom of the flat tip dewar of 135 mm diameter. The gradiometer consists of the DROS and the planar pickup coil. The DROS has a hysteretic dc SQUID (the signal SQUID) and a reference junction in series, shunted by a relaxation circuit consisting of an inductor and a resistor. The pickup coil is a first-order gradiometer with two 12 mm × 12 mm planar coils connected in series and the baseline is 40 mm. The system noise level is below 10 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ in the frequency range above 1 Hz.

2.2 Simulation procedure

The simulation study was done using a spherical conductor model of 100 mm radius. The center of the lower coil of the gradiometers was assumed to be positioned on the xy plane, which is 21 mm high from the outer bottom of dewar and its z coordinate is 125 mm from the center of the sphere. The magnetic fields were generated by a tangential dipole located at 42 mm below the sensor plane. Moment was changed in a sinusoidal pattern with peak amplitude of 10 nA·m to make localization in a wide range of noise-to-signal ratio. Considering a gradiometer with a baseline of 40 mm, dipole fields, B_s, at 40 coil locations were calculated using the formula derived by Sarvas [4], where the contribution of volume current was included. Then measured fields, B, were synthesized by adding background noise fields, B_n, to the dipole fields, and a single dipole was localized from these synthesized fields by solving the inverse problem in Simulated Annealing algorithm. We let here the new dipole fields of the localized dipole be B_d. Finally the distance between the calculated dipole source and the original dipole was defined as the location error caused by the system and background noises. The noise effect on the location error was expressed by the ratio of root-mean-squared noise fields and root-mean-squared dipole fields over 40 channels, which is given by $N/S = \sigma(B_n)/\sigma(B_s)$. In order to assess the calculated dipoles, we used the confidence limit in which the calculated dipoles exist with a 95 % probability. Confidence volume is calculated by a multiplication of confidence limits in x, y and z directions.

For the simulation study, we used brain noises with a subject or system noises without subject as background noises. The brain noises include spontaneous neuromagnetic fields, which were measured in a magnetically shielded room in the same way as the evoked field experiments, keeping the subject's eyes open but without any stimulation. 128 epochs of spontaneous field data in a continuous 1 s period with a sampling frequency of 256 Hz were averaged and digitally filtered below 40 Hz. System noises were measured similarly without subject.

In order to examine the localization accuracy experimentally, we made experiments using a phantom of a spherical conductor of 100 mm radius in which a T-shaped dipole was positioned. Using a 3-dimensional digitizer (ISOTRAK II), the coordinates of the phantom and dewar were measured to define the sensor position in the phantom coordinate with digitizing accuracy of 1.5 mm. Applying ac currents to the dipole, we measured the dipole fields and averaged 100 epochs. Noise fields were measured separately without applying currents.

3 Results

In the dipole source localization, the dipole parameter was determined by minimizing the residual field variance which indicates that the model fits well to the measurements. In Fig. 1, location errors obtained for the brain noises in two subjects and for the system noises are represented as functions of the normalized variance of the residual field, $\sum (B - B_d)^2 / \sum B^2$. We observed that the location errors are well correlated with the normalized variance of residual fields for system noise and brain noises in subject JSC. For brain noise in subject YBU, however, the correlation was rather weak. So it was difficult to justify localization accuracy, which we defined as the upper limit of the location error, by the residual field variance.

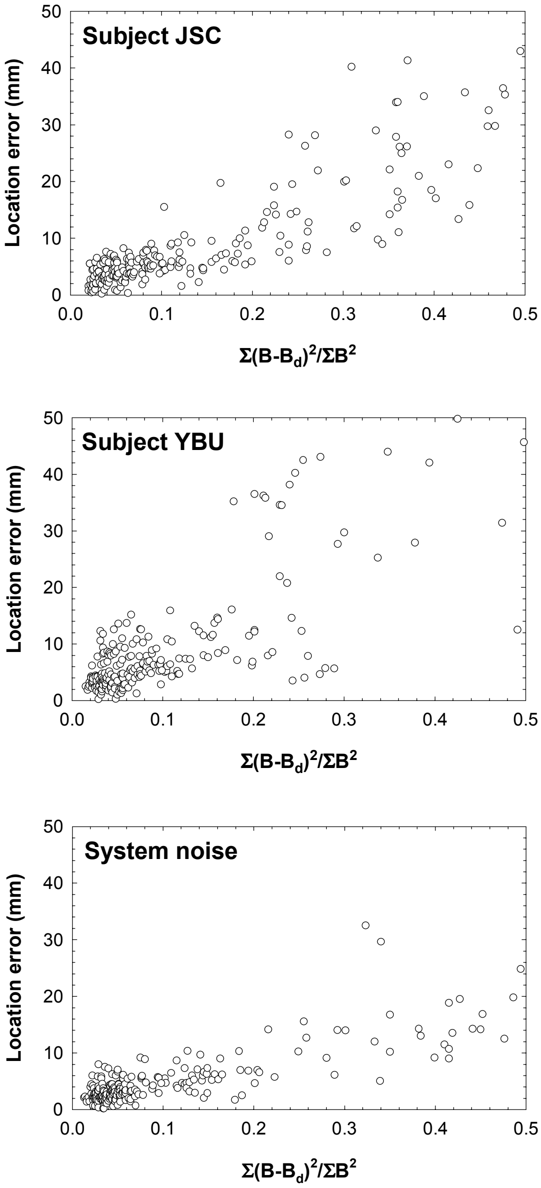

Figure 1: *Relation between the location error and normalized variance of residual fields in the dipole localization. Location errors were obtained from the calculated dipoles using the synthesized fields, where measured brain noises in two subjects (JSC and YBU) and system noise without subject were used as background noises.*

Fig. 2 shows the location errors plotted as functions of *N/S*. Here the open circles represent the data with normalized variance of residual field of less than 0.1. It is interesting to note that location error can be small of less than several mm, even *N/S* is very high of more than 0.5. When we limited *N/S* below 0.3, we could estimate the localization accuracy at 8 mm for all cases. Also we obtained linear relations between confidence volume and *N/S* for calculated dipoles.

In real measurements, however, noise and signal can not be separated and then we used confidence volume of the calculated dipoles as a criterion to determine the localization accuracy. Location errors were represented as functions of confidence volume in Fig. 3. In this figure, we could obtain localization accuracy of 9 mm when we used the criteria with confidence volume of 800 mm^3 and normalized variance of residual field of 0.1. The volume of 800 mm^3 corresponds to a sphere with a radius of less than 9 mm, i.e. is consistent with the location error. Even though a smaller value of confidence volume was taken, we could not get better localization accuracy.

Localization accuracy was also studied as a function of the distance from the center of the bottom of dewar, keeping *N/S* values low using larger moment. The results in Fig. 4 show that if the distance was less than 45 mm, localization accuracy remained within 11 mm.

Experimentally obtained results in the phantom study were also plotted in the figure and agreed well with the simulation results. Small differences may be due to positioning errors of sensors which are located inside helium dewar.

When a dipole with a moment of 20 nA·m was located within 30 mm from the center of the bottom of dewar, we obtained a location error of 5 ± 2 mm.

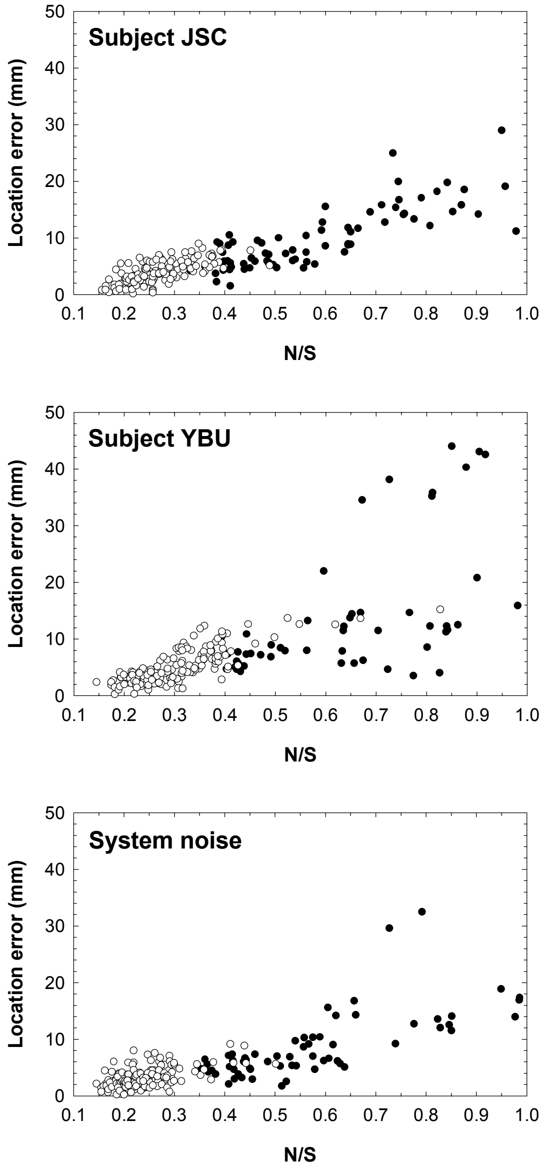

Figure 2: *Location error as a function of rms N/S. Open circles correspond to the data where the normalized variance of residual field is less than 0.1.*

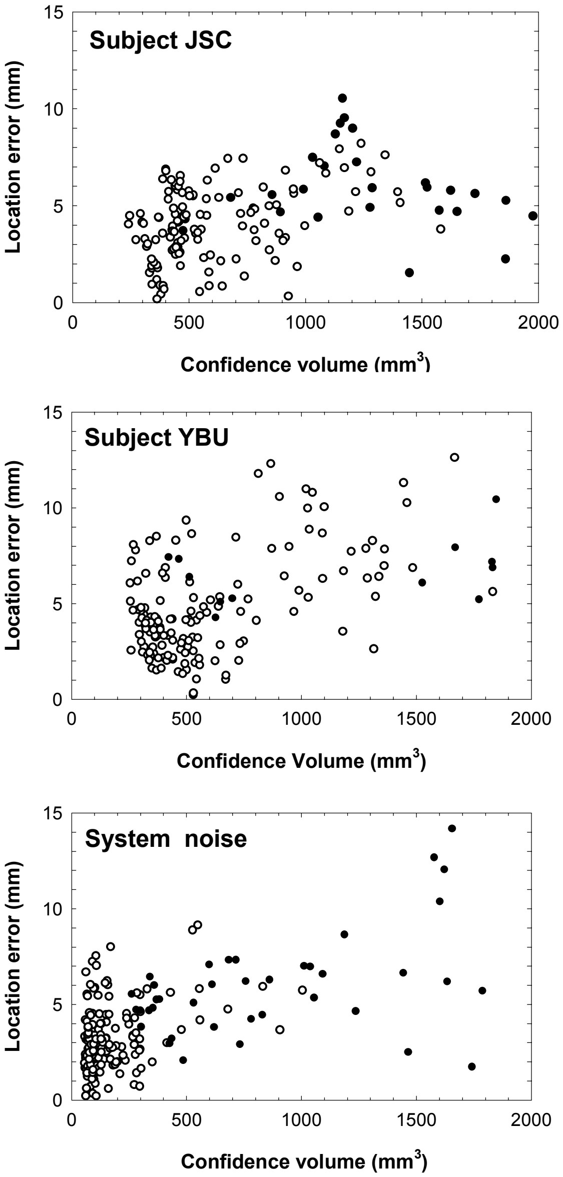

Figure 3: *Relation between location error and confidence volume.*

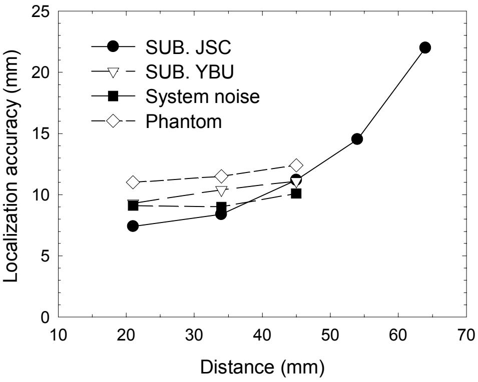

Figure 4: *Localization accuracy as a function of distance from the center of the bottom of dewar.*

4 Conclusion

We evaluated localization accuracy in a spherically homogeneous conductor model using tangential fields. In the simulation study, brain noises measured with our 40-channel system were used as background noises. From the results, we found that location error was well correlated to noise-to-signal ratio, residual field variance and confidence volume. Therefore we could determine the criteria to obtain localization accuracy of 9 mm. It was confirmed experimentally using a phantom head. Experimental results with various positions and moments show that we can estimate a dipole position with an error of 5 ± 2 mm for a dipole located around cortical area of the human brain, indicating that our system can be used to study cortical activities of the human brain.

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